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Accumulation of Atmospheric Sulfur by Plants and Sulfur-Supplying Capacity of Soils

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Accumulation of Atmospheric Sulfur by Plants and Sulfur-Supplying Capacity of Soil

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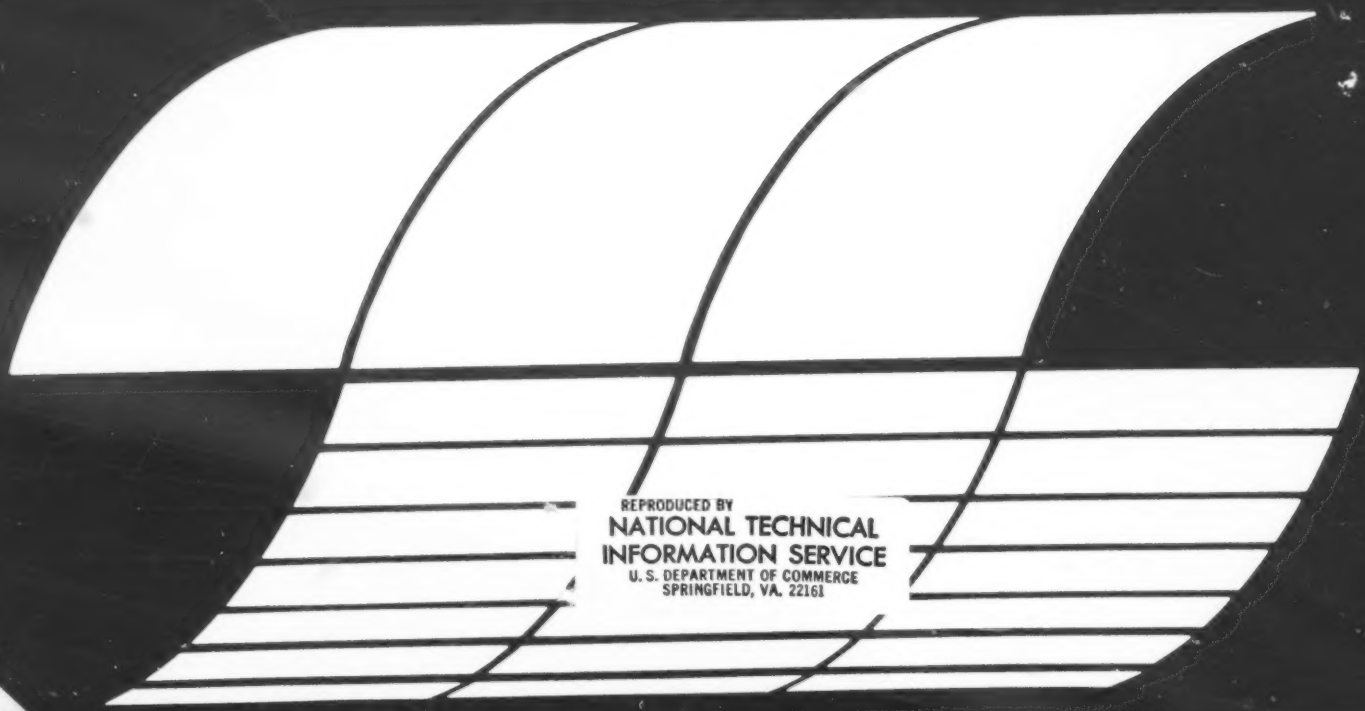

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The Tennessee Valley Authority conducted studies to measure the amount of sulfur (S) that is transferred from the atmosphere to agro-ecosystems and to determine the S-supplying capacity of soils in the Tennessee Valley. Three techniques were tested for determining the fractional contribution of the soil and the atmosphere to the total S content in field-grown plants. Soybeans, cotton, and fescue were grown in equal quantities of the same soil with a low sulfur content at three field locations and in a greenhouse with charcoal-filtered air. Technique III, which provided a direct method for calculating the amount of plant S that was derived from the soil at any location, proved to be satisfactory for measuring the amount of atmospheric S accumulated by plants. Cotton grown 4 and 3 km from coal-fired power plants accumulated 125 and 240 mg S per 100 g, but fescue accumulated only 65 and 58 mg S per 100 g at the same locations. Cotton grown near the power plants produced significantly more biomass than that grown at a location remote to sources of SO_2.

The S-supplying capacity of selected soils was evaluated by measuring the rate of S accumulation by fescue grown in a greenhouse with charcoal-filtered air. The rate of S mineralization in soil collected from a depth of 0 to 30 cm at five sites was about 1 mg per kilogram of soil during the 27 weeks of plant growth.

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ACCUMULATION OF ATMOSPHERIC SULFUR BY PLANTS AND SULFUR-SUPPLYING CAPACITY OF SOILS

by

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ABSTRACT

Sulfur (S) requirements to maintain high crop production range from 10 to 40 kg/ha·yr. A decline in the use of S-containing fertilizers in recent years has placed a greater dependency on the atmosphere as a source of supplemental S to meet the S needs of plants. The Tennessee Valley Authority (TVA) and the U.S. Environmental Protection Agency (EPA) initiated an investigation in 1976 to measure the amount of S that is transferred from the atmosphere to agro-ecosystems and to determine the S-supplying capacity of soils in the Tennessee Valley.

Because a plant can accumulate S from both the soil and the atmosphere, three techniques were tested for determining the fractional contribution of the soil and the atmosphere to the total S in field-grown plants. Soybeans, cotton, and fescue were grown in equal quantities of the same low-sulfur soil at three field locations and in a greenhouse with charcoal-filtered air. The first technique assumed that S uptake from the soil was the same at all locations and that increased S accumulation by field-grown plants over plants grown in the greenhouse was a measure of atmosphere-derived S. This technique proved unsatisfactory because total S uptake was higher in the greenhouse than at a field location. In technique II, an equal amount of fertilizer S, labeled with ^{35}S (a radioactive isotope of S), was applied to the soil in each growth container. The S in each unit weight of plant tissue was partitioned into two parts: (1) S derived from fertilizer and (2) S derived from soil and the atmosphere. Although this technique was useful in demonstrating a source of S other than the soil, the amount of S accumulated from the atmosphere could not be calculated by this method. Technique III provided a direct method for calculating the amount of plant S that was derived from the soil at any location. Soil S was labeled with ^{35}S, and the specific activity (ratio of radioactive S to stable S) was determined by measuring the specific activity of S in plants grown in the absence of atmospheric S. The amount of S accumulated from the atmosphere was obtained by subtracting soil-derived S from total plant S at each field location. This technique proved to be satisfactory for measuring the amount of atmospheric S accumulated by plants. Cotton grown 4 and 3 km from coal-fired power plants accumulated 125 and 240 mg S per 100 g (dry wt), but fescue accumulated only 65 and 58 mg S per 100 g (dry wt) at the same two locations. The cotton grown near the power plants produced significantly more biomass than that grown at a location remote to industrial sources of SO_2, illustrating the importance of atmospheric sulfur as a plant nutrient where the sulfur content of soils may be inadequate to meet plant requirements.

The S-supplying capacity of selected soils was evaluated by measuring the rate of S accumulation by fescue grown in a greenhouse with charcoal-filtered air. The rate of S mineralization in soil collected from a depth of 0 to 30 cm at five sites was about 1 mg/kg of soil during the 27 weeks of plant growth.

This report was submitted by the Tennessee Valley Authority, Office of Natural Resources, in partial fulfillment of Energy Accomplishment Plan 80 BDO under terms of Interagency Agreement EPA-IAG-D8-E721-DO with the Environmental Protection Agency. Work was completed as of December 31, 1977.

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SECTION 1
INTRODUCTION

Sulfur (S) is an essential plant nutrient needed for the synthesis of proteins and other organic compounds within vegetative tissue. The amount of S needed for medium to high crop yields ranges from about 10 to 40 kg/ha·yr.[1] Crops such as corn (Zea mays L.) and wheat (Triticum aestiuum L.) use the lowest amount of S, whereas crops such as cabbage (Brassica oleracea), turnips (Brassica rapa), and alfalfa (Medicago sativa L.) use the highest amount.

Three possible sources of S to meet crop requirements are the soil, fertilizers, and atmosphere. In humid regions, most S in the soil is present as proteinaceous compounds in the soil organic matter, with a lesser amount in inorganic forms in the soil solution and adsorbed on the clay fraction. The S in organic matter is in a chemical form that cannot be used directly by plants. The gradual decomposition of organic matter by soil microorganisms oxidizes proteinaceous S compounds to the sulfate SO_4^{-2} form, which is readily absorbed by plant roots. Although the release of S from soil organic matter has seldom been measured directly, Bettany et al.[2] found that, depending on the characteristics of the organic matter, 30 to 70 percent of the S in alfalfa plants grown in the greenhouse was derived from mineralized S. Because the soils used in this study contained 2 to 6 percent organic matter, these data suggest that only soils high in organic matter content can supply an appreciable percentage of the crop's S needs from decomposition of organic matter. Soil retention of sulfate S is limited to about one year because of leaching and crop removal; consequently, S usually must be added annually to prevent reductions in yield.

Fertilizer materials such as ammonium sulfate, potassium sulfate, and ordinary superphosphate, when applied to soils, usually add adequate S along with the other plant nutrients. However, the recent trend to apply fertilizers with a relatively high N, P, and K content and essentially no S should have resulted in increased occurrences of S deficiency, but this has not been the case. According to Beaton et al.,[3] the only crops that show S deficiencies are usually found on highly leached soils at sites remote from industrial areas. This indicates that the increase in combustion of fossil fuels, which has occurred concurrently with the decrease in application of fertilizer S, may have prevented a significant S shortage by supplying S to plants and soils through the atmosphere.

Sulfur in the atmosphere exists as sulfur dioxide (SO_2) and hydrogen sulfide (H_2S) in a gaseous form and as sulfate in association with aerosols and particulate matter. Sulfur is transferred from the atmosphere to agroecosystems by direct sorption of SO_2 by plants and soil, dry particulate deposition, and rainfall. Numerous investigators have reported that atmospheric SO_2 is absorbed directly by plant foliage. Fried[4] used ^{35}S-labeled SO_2 to demonstrate that alfalfa plants can absorb SO_2 through the leaves and convert it into organic sulfur compounds. Cowling et al.[5] found beneficial effects of SO_2, such as increases in yield and S content, in perennial ryegrass that was grown with an inadequate supply of S to

the roots. Olsen[6] showed that cotton plants grown in an atmosphere containing 0.01 to 0.05 ppm SO_2, although supplied with adequate sulfate in a nutrient solution, still absorbed about 30 percent of their S from the atmosphere. Several investigators[7-10] have reported direct adsorption of SO_2 by soils. Jordan et al.,[11] who extensively surveyed S in precipitation and dry particulate deposition in southern states, reported values of 10 to 30 kg/ha·yr; these values are similar in magnitude to crop requirements.

A comprehensive evaluation of SO_2 control strategies at coal-fired power plants should take into account the economic impact on agriculture if sulfur is significantly reduced in the atmosphere.

To evaluate the economic significance of the atmosphere as a source of S for crop production, the Tennessee Valley Authority (TVA) conducted a study to measure the amount of S transferred from the atmosphere to agro-ecosystems and to determine the S-supplying capacity of soils representative of the Tennessee Valley.

SECTION 2
CONCLUSIONS AND RECOMMENDATIONS

At the beginning of this study, we found that a reliable technique for measuring the amount of S accumulated by crops from the atmosphere was not available. Crops were grown in equal quantities of the same soil near coal-fired power plants, at a remote location, and in a greenhouse equipped with charcoal-filtered air. We experimented with three techniques for measuring the transfer of S from the atmosphere to agro-ecosystems to select the most appropriate one for use in future investigations.

The results of two years' study indicate that labeling the soil S with radioactive ^{35}S has definite advantages over the method of comparing the total S content of plants grown in the presence and absence of atmospheric S. Results from the 1976 study showed no apparent advantage in using S-depleted soil rather than a low-S soil.

Cotton was more efficient than fescue in accumulating S from the atmosphere, as shown by a higher concentration of atmospheric S in cotton than in fescue grown near coal-fired power plants. The amount of S accumulated from the atmosphere was apparently influenced by the level of S supply in the soil relative to the S requirement of the plant. A crop grown in an S-deficient soil will accumulate more S from the atmosphere than the same crop grown in a soil that has an adequate supply of S. Cotton grown in the vicinity of coal-fired power plants accumulated significantly more atmospheric S than was transferred in rainfall and dry deposition, which indicated that 75 to 90 percent of the total S accumulated from the atmosphere was in the form of SO_2. The cotton grown near the steam plants produced significantly more biomass than that grown at a location remote to industrial sources of sulfur, which illustrates the importance of atmospheric sulfur as a nutrient where soil sulfur levels are inadequate to meet plant needs.

The use of sand cultures to measure accumulation of atmospheric S by plants proved satisfactory. In the future, both soil and sand cultures will be used to study the relationship between supply of soil S to the roots and accumulation of atmospheric S by the leaves.

This study supports the use of S accumulation by plants to measure the S-supplying capacity of soils. The S uptake pattern during the 27-week growth period showed a readily available sulfate pool in the soil and a constant rate of S mineralization from the soil organic matter. The size of the sulfate pool varied among soils and was larger in the subsoil than in the topsoil. In the absence of fertilizer S or atmospheric S, the sulfate pool can be replenished only by S that is mineralized from soil organic matter. The rate of S mineralization, measured in the soils of this study, was not great enough to promote maximum plant growth.

Because many field experiments have failed to show a growth response to applied fertilizer S, one can only conclude that atmospheric S prevents depletion of the available sulfate pool in the soil to a level that limits plant growth. This result shows the importance of determining the S-supplying capacity of soils under conditions that eliminate the atmosphere as a source of S to soils and plants.

The economic importance of atmospheric S can be assessed only after the S-supplying capacity of soils and the amount of S transferred from the atmosphere to the agro-ecosystem have been measured. The S requirements of plants relative to the supply of soil S must also be considered. Plants with a high S requirement, when grown on soil with a low S supply, will soon become S-deficient if S is removed from the atmosphere.

After consideration of all these parameters, the consequences of removing a significant amount of sulfur from the atmosphere can be estimated. For example, cotton grown in the containers at Crossville contained 152 mg S. About one-half, or 76 mg, of this S would be removed in the harvested lint and seed. The soil mineralization rate of the soil used in this study (same as soil No. 5 in the S-supplying capacity study) was 1 mg S per kilogram of soil per 27 weeks, or about 45 mg S during the growing season for the 45 kg of soil used. At Crossville, 41 mg S was added to each container as wet-dry deposition from the atmosphere. The contribution of soil mineralization and atmospheric deposition to the sulfate pool is equivalent and totals the estimated amount of S removal in the harvested portion of the crop. Application of fertilizer S for cotton grown on this soil is recommended by the State Agricultural Experiment Station. Any reduction in deposition of atmospheric S must be replaced by an equal amount of fertilizer S to maintain present yields.

The cost of removing S at the power plant and the cost of supplying additional fertilizer to agricultural crops should be considered in establishing emission standards and control technology.

The findings in this study have implications other than that of atmospheric S having an economic significance to crop production. Studies that are designed to measure the effects on plants of chronic exposure to SO_2 must include a consideration of S as a plant nutrient. The S level in the soil in which the plants are grown would be especially critical to the proper interpretation of the results. Additions of fertilizer S or the use of high-S soil would eliminate the potential for observing a growth response to S and, therefore, would not provide an accurate evaluation of the total effect of low-level exposure to SO_2.

Soil and plants provide a "sink" for atmospheric S. The rate of S transfer from the atmosphere to the terrestrial ecosystem will influence the distance that power plant emissions are transported in the atmosphere. A method of measuring atmospheric SO_2 transfer to soils and plants is essential for predicting long-range transport. Because the relationship between soil S supply and crop requirement influences the rate of S accumulation from the atmosphere, these studies should be expanded in this area of investigation.

In this experiment, the sulfate pools in some of the soils were not depleted during the 27 weeks of plant growth. Therefore, fescue has been replanted to extend the growth period for a sufficient time to measure the S-supplying capacities. Other soil types, representative of the Tennessee Valley, will be collected to determine S-supplying capacities. Accumulation of S from the atmosphere by plants will be measured at several locations with technique III (use of ^{35}S-labeled fertilizer to measure the amount of S derived from the soil directly).

SECTION 3
EXPERIMENTAL CONSIDERATIONS AND PROCEDURES

GENERAL CONSIDERATIONS

The approach taken in this investigation is based on the relationship that exists between crop yield and S supply, as illustrated in Figure 1. As the supply of S is increased, crop yield increases to some constant level, at which another growth factor limits further increase in yield. To obtain maximum yield under a given set of environmental conditions, total S supply must at least equal the total S requirement identified as point "A" on the S supply axis. The actual value for point "A" will depend on crop species and yield level. Sulfur supplied in excess of the S requirement cannot be used effectively by crops.

The total S supply, which is the amount of S in a form that is readily available to plants during the growing season, consists of native soil S and supplemental S. The amount of S supplied by the soil, indicated by point "B" in Figure 1, depends on the rate at which S is released during decomposition of soil organic matter and on the size of the "pool" of soluble and adsorbed sulfate. The relative position of point "B" could be at any point on the supply axis, depending on the total S requirement value. For example, a given amount of soil S could supply the total requirement for a relatively low crop yield, but only a part of the requirement for a relatively high crop yield. When the supply of native soil S is less than the total S requirement ($A - B > 0$), thus requiring supplemental S for maximum crop yields, atmospheric S becomes extremely important.

For atmospheric S to affect crop production significantly, supplemental S must be needed, and the S that is transferred from the atmosphere to agro-ecosystems must contribute a relatively large proportion of these supplemental needs. This study (1) investigates three techniques for determining the fractional contributions of the soil and the atmosphere to the total S content of field-grown crops and (2) evaluates a bioassay method for determining the S-supplying capacity of soil from selected sites.

Measurement of Sulfur Transfer from the Atmosphere to Crops

At the beginning of this study, we found that a reliable technique for measuring the amount of atmospheric S accumulated by crops was not available. Three techniques were considered in this study to select the most appropriate one for use in future work. These techniques are summarized in Table 1.

Technique I--

This method of estimating the input of atmospheric S into the agro-ecosystem consists of comparing the total S content of plants grown in the presence and absence of atmospheric S. For this comparison to be

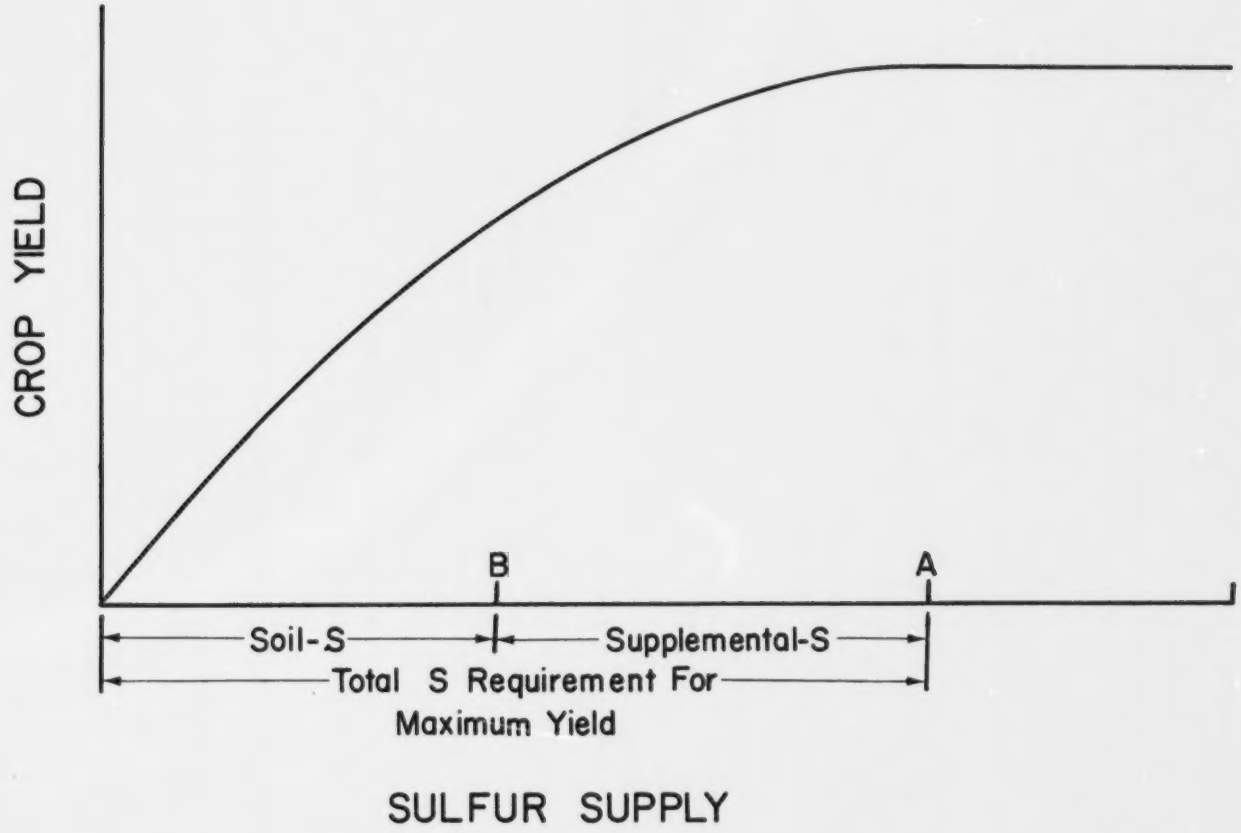

Figure 1. General relationship between sulfur supply and crop yield.

TABLE 1. SUMMARY OF THE TECHNIQUES USED TO MEASURE THE TRANSFER OF SULFUR FROM THE ATMOSPHERE TO CROPS

Item	Technique I	Technique II	Technique III
Basic equation	ATM S = TOTAL PLANT S - SOIL S	$[\text{SOIL S + ATM S}]_{F,G} = [\text{PLANT S}]_{F,G} - [\text{FERT S}]_{F,G}$	ATM S_F = TOTAL PLANT S_F - SOIL S_F
Variables	$[\text{Plant S}]_{F,G}$ = S concentration in plant = (mg/g)	$[\text{Fert S}]_{F,G} = \frac{\text{total cpm } ^{35}\text{S/gdw}}{\text{cpm } ^{35}\text{S/mg S in fertilizer}}$ = (mg S/g, dry wt)	Radioactivity in $\text{plant}_{F,G}$ = total cpm ^{35}S
	$\text{Biomass}_{F,G}$ = g(dry wt)/plant	$[\text{Plant S}]_{F,G}$ = S concentration in plant = mg/g	$[\text{Plant S}]_{F,G}$ = [S] in plant = mg/g
		$\text{Biomass}_{F,G}$ = g(dry wt)/plant	$\text{Biomass}_{F,G}$ = g(dry wt)/plant
Calculations	Total plant S_G = biomass_G X $[\text{plant S}]_G$ = Soil S_G	If $[\text{atm S}]_G = 0$, then $[\text{soil S + atm S}]_G = [\text{soil S}]_G$	Total plant S = [plant S] X biomass
	Total plant S_F = biomass_F X $[\text{plant S}]_F$	Assume: $[\text{soil S}]_G = [\text{soil S}]_F$	
	Assume: Soil S_G = soil S_F	Then: $[\text{soil S + atm S}]_F - [\text{soil S}]_G = [\text{atm S}]_F$	Plant $S^*_G = \frac{\text{Total cpm } ^{35}S_G}{\text{Total plant } S_G}$ = specific activit of available S in $\text{soil}_{G,F}$
	Then: Atm S_F = total plant S_F - soil S_G		Soil $S_F = \frac{\text{Total cpm } ^{35}S_F}{\text{Plant } S^*_G}$
Requirements	1. $\text{Biomass}_G = \text{biomass}_F$	1. $[\text{Soil S}]_G = [\text{soil S}]_F$	1. No source of S in greenhouse other than readily available soil S
	2. No source of S in greenhouse other than readily available soil S	2. The uptake of atmospheric S must not reduce the $[\text{soil S}]_F$	2. Plants must be grown in containers
	3. Soil S_G = soil S_F	3. $[\text{Plant S}]_F = [\text{plant S}]_G$	
	4. Plants must be grown in containers	4. If $[\text{fert S}]_F > [\text{fert S}]_G$, then $[\text{soil S}]_F > [\text{soil S}]_G$ and overestimates $[\text{atm S}]_F$	
		5. Plants must be grown in containers	
		6. No source of S in greenhouse other than readily available soil S	

valid, the amount of S accumulated from the soil by plants grown in the presence of atmospheric S must be the same as that accumulated by plants grown in the absence of atmospheric S. To assure a constant supply of soil S, both sets of plants must be planted in the same amount of uniform soil.

A set of plants grown in a greenhouse equipped with filters to remove all forms of atmospheric S is used to measure the amount of S accumulated from the soil. This value is subtracted from the total S content of plants grown in the field to determine the amount of S accumulated from the atmosphere.

This technique is limited to conditions in which vegetative production in the field is equal to that in the greenhouse.

Technique II--

To eliminate some of the effect of differences in plant size, the source of S in each unit weight of plant material grown in the presence of atmospheric S can be compared with that grown in the absence of atmospheric S. The S per gram of plant material was derived from three possible sources: fertilizer, soil, and atmospheric S. By labeling the fertilizer S with ^{35}S, one can determine the amount of plant S derived from the fertilizer. This technique separates the plant S into two sources--[fertilizer S] and [soil S plus atmospheric S]--and can be used when the concentrations of S in the plants are equal, despite a difference in plant size. The concentration of [soil S plus atmospheric S] in plants grown in the absence of atmospheric S was assumed to be the amount of soil-derived S per unit weight of plant material. This value was subtracted from the concentration of [soil S plus atmospheric S] in plants grown in the field to obtain the amount of atmospheric S accumulated per unit weight of plant material.

Technique III--

This technique provides a direct method for calculating the amount of plant S derived from the soil. Basically, it consists of determining the specific activity of available soil S in the absence of atmospheric S and using this value to calculate soil-derived S in plants grown at any location.

Before planting, a sufficient quantity of soil was thoroughly mixed and divided equally into growth containers; consequently, available native soil S was the same in all containers. An equal amount of fertilizer S, labeled with ^{35}S, was added to each growth container thereby establishing an unknown specific activity of the combined fertilizer S and sulfate pool in the soil. It is not necessary to know the specific activity of the fertilizer S with this technique. Plants accumulated S from these two sources in the same proportion as the sources occurred in the soil; therefore, if the fertilizer and soil were the only sources of S, the specific activities of plant S and soil S were the same. Soil S, as used in this technique, included both fertilizer S and soil S.

The accumulation of atmospheric S is calculated by three steps: (1) Divide the total radioactivity by total plant S in plants grown in the absence of atmospheric S to obtain the specific activity of the soil S; (2) divide the total radioactivity of plants grown in the field by the specific activity of the soil S to obtain the amount of soil-derived S in the field plants; (3) subtract soil-derived S from total S in the field-grown plants to obtain the amount of S accumulated from the atmosphere.

Measurement of Sulfur-Supplying Capacity of Soils

The S fractions in soil available for use by plants include (1) the soluble inorganic sulfate, (2) the sulfate adsorbed on clay surfaces, and (3) part of the organic S that is mineralized from the soil organic matter during the growing season. In this study, a distinction is made between S supply and the S-supplying capacity of a soil. The S supply consists of a sulfate pool that includes the soluble and adsorbed sulfates in the soil. Beaton et al.[12] reviewed the chemical extractions that have been suggested for estimating the amount of soluble and adsorbed sulfates in soil. The size of the sulfate pool is finite, and in many soils the sulfate pool contains only one or two times the annual S requirement of crops. Therefore, additions to the sulfate pool are required to maintain maximum crop production for an extended time. The S-supplying capacity of a soil is the rate at which S moves into the sulfate pool by mineralization from the soil organic matter. Assessment of S-supplying capacity of soils based on data from field experiments is difficult because of the inability to evaluate the contribution of atmospheric S to the sulfate pool.

The rate of S uptake by plants can be used to estimate the S-supplying capacity of soils. Plants have been shown to deplete the sulfate pool in a fixed amount of soil in greenhouse pots. Therefore, the rate of uptake after depletion of the sulfate pool can be used as a measure of the rate of S mineralization from soil organic matter. This study was conducted in a greenhouse equipped with charcoal filters for removing atmospheric S.

EXPERIMENTAL PROCEDURES

Field studies were conducted in 1976 and 1977 to evaluate the three techniques for measuring the transfer of S from the atmosphere to crops. The S-supplying capacity of selected soils was measured in a greenhouse experiment.

Field Study--1976

Growth containers were prepared by cutting 15-cm-diam, polyvinyl chloride (PVC) pipe into 90-cm lengths and covering one end with a standard PVC cap; 20 kg of soil was placed in each container to within 15 cm of the top.

Soil Preparation and Treatment--

Method I--A quantity of Hartsells fine sandy loam (fine-loamy, siliceous, thermic, Typic Hapludults) soil with a very low S content was collected at the Auburn University Agriculture Experiment Station in De Kalb County, Alabama. This facility is located about 70 km SSW of the TVA Widows Creek coal-fired power plant. The soil was mixed thoroughly and placed in nine PVC growth containers; 5 g of concentrated superphosphate (CSP) and 2 g of potassium chloride (KCl) were mixed into the top 30 cm of soil. This soil is referred to as "low-S soil."

Method II--Because the source of S in plants was to be determined by a difference in the total S content, a reduction in soil S before growing the experimental plants might make the measurements more precise. A quantity of Hartsells fine sandy loam was collected from a site in Colbert County, Alabama, limed to pH 6.5, and placed in greenhouse pots. All nutrients needed for maximum growth, except S, were added and all pots were seeded to corn. After seven weeks of growth, the plants were harvested at the soil surface and discarded. The pots were again seeded to corn. This procedure was repeated until the corn showed visual symptoms of extreme S deficiency, indicating depletion of the readily available soil S. The soil was removed from the pots, separated from the plant roots, thoroughly mixed, and placed in 18 PVC growth containers; 5 g of CSP and 2 g of KCl were mixed into the top 30 cm of soil in each container. This soil is referred to as "S-depleted soil."

Method III--One gram of normal superphosphate containing 127 mg S, labeled with 1.5 mCi ^{35}S per milligram of sulfur, was mixed into the top 30 cm of soil in nine of the growth containers prepared by method II.

Experiment Establishment--

Three replicates of each method of soil preparation were installed at three locations. The first site, located 4 km from the TVA Widows Creek coal-fired power plant, is frequently exposed to relatively high levels of SO_2. The second site was at the Auburn University Agriculture Experiment Station, 70 km SSW of Widows Creek Power Plant, where only background levels (<0.05 ppm) have been recorded, and the third location was in a greenhouse equipped with charcoal-filtered air supply at Muscle Shoals, Alabama.

At the field locations, the growth containers were inserted vertically in the soil, with the tops of the cylinders 15 cm above the soil surface. In the greenhouse, the growth containers were supported vertically in a rack and exposed to the greenhouse air. Eight soybean seeds were planted in each growth container on June 15, 1976, and thinned to two per container after a stand was established. Field-grown soybeans were exposed to natural precipitation, but supplemental deionized water was added as needed to maintain soil moisture above the wilting point. Deionized water was added to greenhouse-grown soybeans as needed to maintain a moisture content of the soil approximating field capacity.

A collector, with the same area as a growth container, was installed at each field location to measure the amount of S deposited in rainfall and as dry particulate into each container.

The entire portion of the soybean plants above ground was harvested on September 15, 1976, dried at 70°C in a forced-air oven, and ground to pass a 20-mesh screen. The concentration of plant S was measured with the Leco furnace method.[13] In method III, the radioactivity, as counts per minute, was determined simultaneously in the plant material and in a sample of the ^{35}S-labeled, normal superphosphate. The specific activity of the fertilizer was calculated as counts per minute per milligram of S, and the amount of fertilizer-derived S in the plant tissue was calculated by dividing the total radioactivity in the plant by the radioactivity per milligram of S in the fertilizer.

Field Study--1977

The results of the 1976 study were used to modify the technique in 1977.

Growth Containers--

Results of the 1976 study showed that a drainage system in the growth containers was essential to prevent the soil from remaining water-saturated for an extended time after a heavy rain. Because sulfate is water-soluble and will readily leach from soil, a system was devised by which the leachate was collected and returned to the soil after the moisture content had been reduced below field capacity. Plastic pots, 30 cm in diameter and 60 cm high, were prepared by sealing a hose connector near the bottom of the sidewall. The growth containers were placed in the field as shown in Figure 2. A 50-gallon garbage can was placed in the soil, with the top about 10 cm above the soil line. Four growth containers were placed symmetrically around the garbage can at a distance of 50 cm. Tygon tubing, 10-mm inside diameter, was fastened to the hose connector on each growth container and passed through a hole in the wall of the garbage can to one of four polyethylene bottles inside. The tygon tube passed through a rigid 1-in. PVC pipe, extending from the growth container to the garbage can, to prevent collapse of the tygon tube due to compression of the soil. The garbage cans were covered with lids, except during transfer of the leachate back to the growth containers.

Soil Preparation and Treatment--

A sufficient quantity of low-S soil to fill 32 of the growth containers was collected from the site described in method I of the 1976 study and mixed thoroughly. A 5-cm layer of gravel was placed in the bottom of each growth container, and 45 kg of soil was added to within 10 cm of the top.

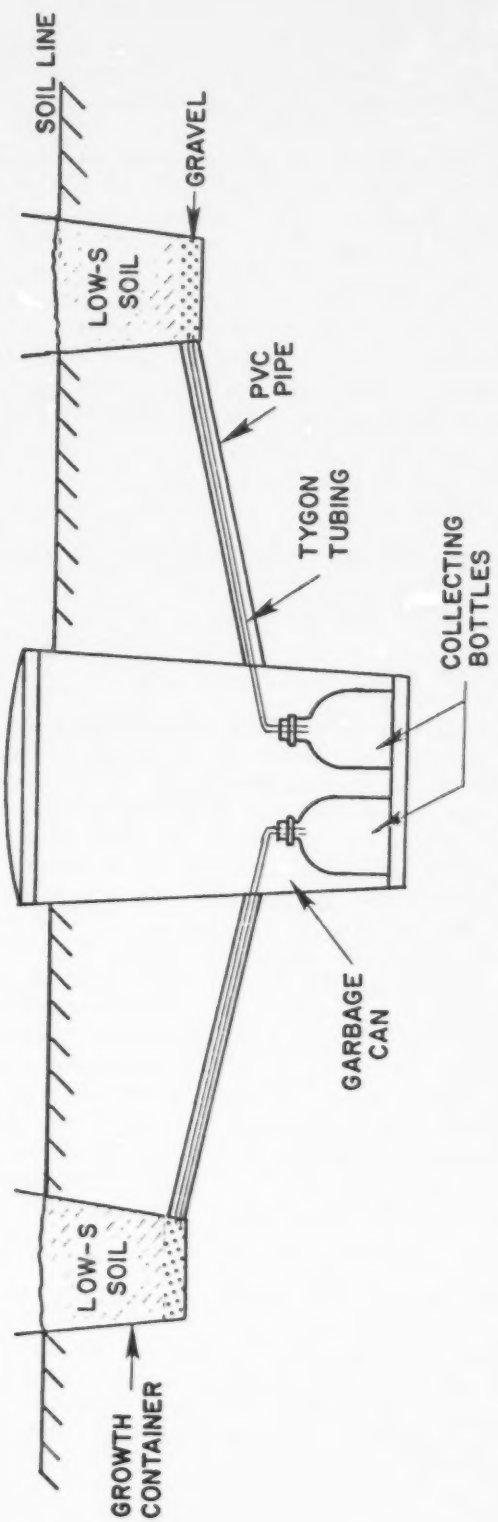

Figure 2. Diagram of experiment installation in the field.

The top 15 cm of soil was removed and mixed with four fertilizer materials: 3.50 g nitrogen (N) as ammonium nitrate; 2.38 g phosphorus (P) and 3.00 g potassium (K) as KH_2PO_4; 1.00 g magnesium (Mg) as magnesium chloride; and 100 mg S as potassium sulfate in solution, labeled with 3.2 mCi ^{35}S per gram of S. The treated soil was returned to the growth container.

Sand Culture--

Although the soil used in this study was low in soluble S, an unknown amount of S was mineralized from soil organic matter during the growing season. A sand culture was included at one field site to test the feasibility of using a growth medium in which the S supply could be better controlled. Soil has a higher moisture-holding capacity than sand, and the frequency of supplemental irrigation required for optimum growth was a major concern. Eight growth containers were prepared as described above, except that sand was used instead of soil.

Nutrient Solution--Deionized water was used to prepare 1 L of each stock salt solution, which was then stored in polyethylene bottles. The salts used and the amounts (in grams per liter) of each were NH_4NO_3, 60.4; $Ca(NO_3)_2$, 131.2; KH_2PO_4, 334.8; $MgCl_2$, 75.2; H_3BO_3, 2.86; $MnCl_2 \cdot 4H_2O$, 1.81; $ZnSO_4 \cdot 5H_2O$, 0.22; $CuSO_4 \cdot 5H_2O$, 0.08; $H_2MoO_4 \cdot H_2O$, 0.02; $FeSO_4$, 5.00.

The nutrient solution was prepared by transferring 100 mL of each stock salt solution to a polyethylene container and diluting to a final volume of 20 L with deionized water. Each sand culture received 2.5 L of the nutrient solution just before planting and every 7 to 10 days thereafter until eight applications were received. Also, 100 mg S, as potassium sulfate in solution and labeled with 3.2 mCi ^{35}S per gram of S, was applied just before planting.

Site Location--

Eight growth containers with soil were installed at each location used in 1976. Eight soil containers and eight sand cultures were also installed near TVA's coal-fired Colbert power plant. This site was selected because its location, about 20 km from Muscle Shoals, would allow supplemental irrigation of the sand cultures. Site designations and locations are shown in Table 2.

Experiment Establishment and Data Collection--

Four replicates each of cotton (Gossypium hirsutum L.) and tall fescue (Festuca arundinaces Schreb.) were planted in the growth containers on May 17, 1977. Cotton was thinned to four plants per container after a stand was established.

TABLE 2. LOCATIONS OF EXPERIMENTAL GROWTH CONTAINERS

Site designation	Location
Widows Creek	4 km SE of the TVA Widows Creek coal-fired power plant near Stevenson, Alabama
Crossville	At the Auburn University Experiment Station near Crossville, Alabama, and 70 km SSW of Widows Creek Power Plant
Colbert	3 km N of the TVA Colbert coal-fired power plant near Barton, Alabama
Greenhouse	Air Quality Research greenhouse at Muscle Shoals, Alabama

During heavy rainfall, water drained through the growth medium to the collecting bottles inside the garbage can. This drainage water was returned to its respective growth container after the soil moisture content had been reduced below field capacity by evapotranspiration. Supplemental irrigation was provided in the field by adding deionized water as needed to maintain adequate soil moisture. Deionized water was added daily to maintain optimum soil moisture in the greenhouse.

The entire portion of the plants above ground was harvested on August 29, 1977, dried at 70°C for 72 h in a forced-air oven, weighed, and ground to pass a 20-mesh screen. Plant S concentration was measured with the Leco furnace method, and radioactivity assay was made on the same sample. The potassium sulfate fertilizer solution labeled with ^{35}S was analyzed for both stable and radioactive sulfur. The specific activity (the ratio of ^{35}S to ^{32}S) of the fertilizer solution, expressed as counts per minute per milligram of S, was calculated by dividing the total counts per minute by the total S content. Experimental protocols used in 1976 and 1977 are summarized in Table 3.

Sulfur-Supplying Capacity of Soils

A quantity of soil was collected from two depths--0 to 30 cm and 30 to 60 cm--at each location shown in Table 4.

TABLE 3. SUMMARY OF EXPERIMENTAL PROTOCOLS USED IN 1976 AND 1977

Growth medium preparation	Site location	Year	Crop	Data analysis
Method I low-S soil	4 km from Widows Creek[a] 70 km from Widows Creek[a] Greenhouse (Muscle Shoals)	1976	Soybeans	Technique I
Method II S-depleted soil	4 km from Widows Creek[a] 70 km from Widows Creek[a] Greenhouse (Muscle Shoals)	1976	Soybeans	Technique I
Method III S-depleted soil + 100 mg S labeled with ^{35}S	4 km from Widows Creek[a] 70 km from Widows Creek[a] Greenhouse (Muscle Shoals)	1976	Soybeans	Technique II
Low-S soil + 100 mg S labeled with ^{35}S	4 km from Widows Creek[a] 70 km from Widows Creek[a] 3 km from Colbert[a] Greenhouse (Muscle Shoals)	1977	Cotton, fescue	Techniques I, II, and III
Sand culture--nutrient solution labeled with ^{35}S	3 km from Colbert[a]	1977	Cotton, fescue	Technique III

[a]Coal-fired power plants.

TABLE 4. COLLECTION SITES FOR SOIL USED IN EXPERIMENT TO DETERMINE SULFUR-SUPPLYING CAPACITY

Site number	Location relative to Widows Creek Power Plant	
	Distance (km)	Azimuth (degrees)
1	3.0	102
2	3.6	158
3	6.3	220
4	44.0	190
5	70.0	200
6	31.0	272
7	9.0	348

Soil Treatment--

The soil from each location and depth was mixed individually with sufficient $CaCO_3$ to adjust the pH to 6.0 to 6.5. Three sulfur-free fertilizers were mixed with 6-kg (oven-dry weight) portions of each test soil: 3 g ammonium nitrate, 4.37 g CSP, and 1.9 g KCl. These materials provided 1 g each of N, P, and K.

A control treatment that would supply sufficient S for optimum growth was prepared with soil collected from the top 15 cm of Mountview silt loam. This soil received the same amount of ammonium nitrate and CSP as the test soil; 1 g K and 200 mg S were supplied as potassium sulfate.

After each harvest, 500 mg N and 500 mg K, as a solution of ammonium nitrate and potassium chloride, were added to each test soil, and 500 mg N, 500 mg K, and 200 mg S, as a solution of ammonium nitrate and potassium sulfate, were added to the control soil.

Experimental Procedure--

Duplicates of each test soil and the control were placed in 10-in. greenhouse pots and planted to Kentucky 31 fescue on November 18, 1976. Soil moisture content was maintained at 20 percent by daily weighing the pots and adding the amount of deionized water necessary to return the weight to the predetermined level.

Four weeks after plant emergence, vegetative growth was harvested 5 cm above the soil surface and allowed to regrow. Additional harvests were made at 8, 12, 16, 21, and 27 weeks after emergence. Plant material was dried at 70°C in a forced-air oven, weighed, ground to pass a 20-mesh screen, and analyzed for S with the Leco furnace method. Cumulative S was calculated by adding the S content of a harvest to the total S in all previous harvests.

SECTION 4
RESULTS AND DISCUSSION

SULFUR TRANSFER FROM ATMOSPHERE TO AGRO-ECOSYSTEM

The field data are presented in chronological order to demonstrate the development of a technique to measure S transfer from the atmosphere to the agro-ecosystem.

Field Study--1976

Technique I--

The total S contents of soybeans grown at three locations and in soil prepared by three methods were used to evaluate this technique (Table 5).

TABLE 5. VEGETATIVE PRODUCTION AND SULFUR CONTENT OF SOYBEANS GROWN AT THREE LOCATIONS IN SOIL PREPARED BY THREE METHODS

Soil preparation	Location	Oven-dry weight (g)	Sulfur concentration (%)	Total sulfur (mg)
I--Low-S soil	4 km[a]	13.3	0.143	19
	70 km[a]	17.0	0.163	28
	Greenhouse	64.0	0.097	62
II--S-depleted soil	4 km[a]	17.3	0.153	27
	70 km[a]	25.0	0.110	28
	Greenhouse	91.6	0.080	73
III--S-depleted soil + 100 mg S	4 km[a]	27.0	0.153	41
	70 km[a]	26.0	0.137	36
	Greenhouse	93.3	0.140	131

[a]Distance from coal-fired power plant.

Dry matter yields, in terms of biomass, for soybeans grown at the field locations were only 20 to 30 percent of those for soybeans grown in the greenhouse. A lack of free drainage through the growth containers, which resulted in temporary flooding after heavy spring rains, caused the growth rates of soybeans to be lower in the field than in the greenhouse.

The validity of this technique depends on the amount of plant S derived from the soil being the same in both the presence and absence of atmospheric S. In this experiment, soybeans were grown in the greenhouse to obtain a value for soil-derived S for use at all locations. The greenhouse plants were found to contain two to three times as much S as the field plants, primarily because the vegetative production was higher in the greenhouse than in the field. Therefore, the total S content of plants grown in the absence of atmospheric S could not be used as a true value for soil-derived S in plants grown in the presence of atmospheric S. Estimating the accumulation of atmospheric S by this technique is questionable if biomass differs between growth sites.

Technique II--

Data from soybeans grown in the soil prepared by method III were used to test the value of this technique for estimating accumulation of atmospheric S by plants. These plants meet the requirement that concentrations of plant S must be similar at all locations.

The concentration of plant S derived from the fertilizer was calculated by dividing the total radioactivity in 1 g of plant material by the specific activity of S in the fertilizer. The concentration of [soil S plus atmospheric S] was obtained by subtracting [fertilizer S] from [plant S] (Table 6).

TABLE 6. SOURCES OF SULFUR IN SOYBEANS GROWN AT THREE LOCATIONS

Location	Plant S (mg/100 g, dry wt)	Fertilizer S (mg/100 g, dry wt)	Soil S plus atmospheric S (mg/100 g, dry wt)
4 km[a]	153	58	95
70 km[a]	137	82	55
Greenhouse	140	67	73

[a]Distance from coal-fired power plant.

If the accumulation of atmospheric S by soybeans grown in the greenhouse were completely eliminated, the value for [soil S plus atmospheric S] in greenhouse plants was the concentration of S derived from the soil. With this technique, it was assumed that the concentration of soil-derived S in greenhouse and field plants was the same and that [atmospheric S] in field plants was equal to [soil S plus atmospheric S] in field plants minus [soil S] in greenhouse plants. In this experiment, the concentration of soil-derived S in greenhouse soybeans was higher

than the concentration of soil S plus atmospheric S in soybeans grown 70 km from the power plant. Therefore, the data from soybeans grown in the greenhouse are not a correct estimate of the amount of S derived from the soil at the other sites.

The higher value for [soil S plus atmospheric S] in greenhouse plants, as compared with that in soybeans grown 70 km from the power plant, may have been due to a higher rate of S mineralization from soil organic matter or to another source of S in the greenhouse. The rate of S mineralization may have been higher in the greenhouse than in the field because the sides of the growth containers were exposed to the greenhouse air and because soil temperature would have been higher in the greenhouse. Decomposition of soil organic matter increases as the soil temperature increases. The presence of very low concentrations of SO_2 in the atmosphere is also a possible source of S since the greenhouse is located only 20 km from the TVA Colbert coal-fired steam plant. In the summer, temperature in the greenhouse is controlled by moving air through a bank of charcoal filters, through evaporative cooling pads, across the plant growing area, and out the opposite side. The system operates almost continuously during daylight hours in the summer, and any trace of SO_2 in the ambient air could result in a measurable accumulation of S by plants.

Because soil containers were inserted into the soil in the field, the rates of S mineralization, and thus the concentrations of soil-derived S, at the two field sites should have been similar. The soybeans grown 4 km from the power plant accumulated 40 mg more S per 100 g (dry wt) than did the soybeans grown at 70 km. The difference in the means at the two field locations is statistically significant at the 97.5 percent confidence level.

Field Study--1977

Data from cotton and fescue grown in 1977 are presented in detail to evaluate the advantages and disadvantages of three techniques for measuring accumulation of atmospheric S by plants.

Cotton--

Technique I--Total biomass and S content of cotton grown at four sites were used to estimate accumulation of atmospheric S by plants by measuring the difference in total S content between plants grown in the presence of atmospheric S and those grown in the absence of atmospheric S (Table 7).

Some variability between replicates is expected in an experiment of this type, but apparent anomalies that appeared at three growth sites require special attention. Vegetative production and S concentration of the cotton in replicate 4 at Crossville and replicate 3 at Widows Creek were higher than in the other replicates at the respective sites. Although several factors could have caused a higher growth rate, the increased S concentration in the plant concomitant with the higher yield

indicates a source of S for these plants that was not available to plants in the other replicates. The source of the additional S was either the soil or the atmosphere, and data presented later in the report will show that it was not the soil. At Colbert Steam Plant, cotton grown in replicate 2 with both the soil and sand culture had lower dry weight, S concentration, and total S uptake than did cotton grown in the other replicates at their respective sites. This indicates that plants grown in replicates 1, 3, and 4 accumulated S from a source other than the soil or sand more readily than did those in replicate 2.

All four replicates at each growth site were used in calculating the mean for each parameter in Table 7 to demonstrate this technique of estimating the contribution of atmospheric S to the total plant S. The mean for total plant S is a mean of the four replicate values rather than a product of mean oven-dry weight and S concentration.

Cotton was grown in a greenhouse with charcoal-filtered air to obtain a value of S accumulation from the soil that could be used as an estimate of soil-derived S in cotton grown at each field site. The amount of S accumulated by field-grown cotton in excess of the amount accumulated by greenhouse-grown cotton was considered to be the amount of S accumulated from the atmosphere.

Total S in cotton grown in the greenhouse was higher than that in cotton grown at Crossville, partly because of a larger biomass, but also because of the higher concentration of plant S in the greenhouse cotton. Therefore, estimating the amount of atmospheric S in cotton grown at Crossville by measuring the difference in total plant S in the two sets of plants was not possible. Although the total plant S in cotton grown in soil at Widows Creek and Colbert Steam Plants was higher than that in cotton grown in the greenhouse, the validity of using S content of greenhouse cotton as an estimate of soil-derived S at those locations was questionable.

Although the use of this technique is limited when measuring the amount of atmospheric S accumulated by plants, a proper interpretation of differences in S concentrations between plants grown at different sites, but with the same supply of soil S, will show the presence of a source of S other than the soil. Results of the 1976 study (Table 5) showed that, when soybean plants were grown with a limited supply of S (soil preparation methods I and II), the higher biomass of greenhouse plants was associated with a reduction in S concentration in the plant tissue, indicating a dilution of plant S because of increased growth. When fertilizer S was applied, the S concentration in the larger greenhouse plants was similar to that in the smaller plants grown in the field. These observations, plus a knowledge of basic principles of plant mineral nutrition, led to the conclusion that, when plants are grown with a finite supply of S, an increase in biomass is associated with a concentration of plant S that is equal to or lower than that in plants with the smaller biomass. An increase in both biomass and concentration of plant S strongly suggests a supply of S from some source other than the soil.

TABLE 7. VEGETATIVE PRODUCTION AND SULFUR CONTENT OF COTTON GROWN AT FOUR SITES

Site	Replicate	Oven-dry weight (g)	Sulfur concentration (%)	Total plant S (mg)
Crossville	1	87	0.11	96
	2	90	0.11	99
	3	88	0.12	106
	4	204	0.15	306
	Mean	(117)	(0.12)	(152)
Widows Creek	1	112	0.15	168
	2	136	0.16	218
	3	244	0.32	781
	4	125	0.13	162
	Mean	(154)	(0.19)	(332)
Colbert (soil)	1	396	0.30	1188
	2	182	0.24	437
	3	412	0.33	1360
	4	436	0.25	1090
	Mean	(356)	(0.28)	(1019)
Colbert (sand)	1	222	0.28	622
	2	115	0.15	172
	3	201	0.28	563
	4	207	0.30	621
	Mean	(186)	(0.25)	(494)
Greenhouse	1	170	0.15	255
	2	173	0.18	311
	3	140	0.22	308
	4	158	0.19	300
	Mean	(160)	(0.18)	(293)

In 1977, the total biomass of cotton was not the same at all growth sites (Table 7). Although these differences could have been caused by a number of environmental factors, the simultaneous increase in both plant S and biomass indicates accumulation of S from the atmosphere and a possible growth response to atmospheric S. Jordan and Bardsley[14] reported a "critical" S concentration of 0.20 percent for cotton; the plants with the lower weights in this experiment also had S concentrations below the critical level.

Technique II--The second technique for measuring the accumulation of S from the atmosphere consists of separating the plant S into two sources--[fertilizer S] and [soil S plus atmospheric S].

The anomalies within replicates shown in Table 7 are again apparent in the data in Table 8. In replicate 4 at Crossville and replicate 3 at Widows Creek, the concentration of plant S and the amount of S in each gram of plant material that was derived from the [soil S plus atmospheric S] was higher than in the other replicates at the respective sites. This observation is significant because of the manner in which the concentration of plant S and the fertilizer-derived S changed as a result of the increased growth. It was concluded above that, if the S supply were finite and low, increased growth would result in dilution of plant S. The concentration of fertilizer-derived S in cotton was lower in replicate 4 at Crossville and replicate 3 at Widows Creek, which shows that this source of S was diluted in the plant tissue, as would be expected with the increased growth. The soil-derived S should also have been diluted in the plant tissue to the same extent as the fertilizer S; therefore, a higher value for [soil S plus atmospheric S] would represent a decrease in soil S and an increase in atmospheric S. The same reasoning applies for interpreting the anomalies at Colbert.

If atmospheric S in greenhouse cotton was zero, the value of [soil S plus atmospheric S] was the concentration of soil-derived S in the plant. If soil S in a unit weight of plant material is assumed to be the same at all locations, then the amount of S accumulated from the atmosphere can be calculated by subtracting soil S in greenhouse cotton from [soil S plus atmospheric S] in field cotton. In this experiment, the concentration of soil S in greenhouse cotton was higher than the concentration of S from all sources in cotton grown at Crossville; therefore, the greenhouse data are not a correct estimate of the amount of S derived from the soil at the other sites.

Although the accumulation of atmospheric S by plants cannot be quantified by this technique, it has some advantages over technique I in demonstrating that a greater amount of atmospheric S was accumulated by plants growing at one site relative to those growing at another site. Plants that accumulate the higher amount of atmospheric S will always have a higher concentration of [soil S plus atmospheric S] and an equal or lower concentration of fertilizer S than plants that accumulate the lower amount of atmospheric S. This relationship is independent of the total amount of S in the plant.

TABLE 8. SOURCES OF SULFUR IN COTTON GROWN AT FIVE SITES

Site	Replicate	Radioactivity (cpm/g, dry wt)	Fertilizer S (μg/g, dry wt)	Plant S (μg/g, dry wt)	Soil S plus atmospheric S (μg/g, dry wt)
Crossville	1	301,140	176	1100	924
	2	345,960	202	1100	898
	3	348,090	204	1200	996
	4	194,400	114	1500	1386
	Mean		(174)	(1225)	(1051)
Widows Creek	1	311,220	182	1500	1318
	2	339,200	198	1600	1402
	3	114,240	67	3200	3133
	4	247,470	145	1300	1155
	Mean		(148)	(1900)	(1752)
Colbert (soil)	1	66,080	39	3000	2961
	2	249,690	146	2400	2254
	3	60,000	35	3300	3265
	4	100,300	59	2500	2441
	Mean		(70)	(2800)	(2730)
Colbert (sand)	1	65,520	38	2800	2762
	2	189,970	111	1500	1389
	3	58,560	34	2800	2766
	4	57,840	34	3000	2966
	Mean		(54)	(2525)	(2471)
Greenhouse	1	202,120	118	1500	1382
	2	133,560	78	1800	1722
	3	253,260	148	2200	2052
	4	235,620	138	1900	1762
	Mean		(120)	(1850)	(1730)

In this experiment, cotton growing near coal-fired power plants had a higher concentration of [soil S plus atmospheric S] and a lower concentration of fertilizer S than cotton grown at Crossville, which is located 70 km from the nearest power plant. The source of S in the growth medium of cotton grown in sand at Colbert was limited to the fertilizer, and with soil S equal to zero, the value for [soil S plus atmospheric S] is the amount of S accumulated in each gram of plant material from the atmosphere.

Technique III--Cotton was grown in a greenhouse with charcoal-filtered air to establish the specific activity of available soil S, but data in Tables 7 and 8 indicate that these plants accumulated S from some other source--either the atmosphere or the soil organic matter.

The relative dilution of the specific activity at the various growth sites was tested by dividing total plant S into the total radioactivity at each site. The mean values for specific activity of plant S at the four sites were (1) Crossville, 25.15 x 10^4 cpm/mg S; (2) Widows Creek, 16.14 x 10^4 cpm/mg S, (3) greenhouse, 11.20 x 10^4 cpm/mg S, and (4) Colbert (soil), 4.61 x 10^4 cpm/mg S. Colbert (sand) was not included because the specific activity of S in the plants that was derived from the growth medium was the same as the specific activity of the fertilizer. The specific activity of S in cotton grown at Crossville was the highest, which showed that greater dilution occurred at the other sites because of S accumulation in the plants from a source other than the soil. Continuous monitoring at the Crossville site showed no measurable concentration of SO_2 in the ambient air, but 41 mg S was deposited by rainfall and particulate deposition on a surface area equal to the growth containers. At Widows Creek and Colbert, 30 and 47 mg S, respectively, were deposited in this manner. Although cotton at Crossville probably accumulated some S from the atmosphere, the specific activity of plant S was more comparable to the specific activity of soil S than at any other location. Therefore, the specific activity of plant S at Crossville was assumed to be equal to the specific activity of soil S at the other sites for the purpose of demonstrating this method of calculating S accumulation from the atmosphere.

The specific activity of S in cotton grown at Crossville was calculated by dividing total radioactivity by total plant S for each replicate (Table 9). The value for specific activity in replicate 4, which is much lower than values for the other replicates, is further evidence of a source of S other than the soil for cotton grown in that container.

The total radioactivity of cotton in each replicate at the other sites was divided by the mean specific activity of S in cotton grown at Crossville to obtain the amount of soil-derived S in the plants (Table 10). Soil-derived S in cotton grown in sand culture at Colbert was calculated by dividing the total radioactivity in the plants by the specific activity of the fertilizer (171 x 10^4 cpm/mg S).

Evaluation of the data from Widows Creek by using techniques I and II indicated that cotton in replicate 3 accumulated S from some source other than the soil. The data in Table 10 show that a much larger percentage of the total plant S was derived from the atmosphere in replicate

TABLE 9. DETERMINATION OF SPECIFIC ACTIVITY OF SULFUR IN COTTON GROWN AT CROSSVILLE

Replicate	Total radioactivity (cpm x 10^4)	Total plant S (mg)	Specific activity (cpm x 10^4/mg S)
1	2620	96	27.29
2	3114	99	31.45
3	3063	106	28.89
4	3966	306	12.96
Mean			(25.15)

TABLE 10. SOURCE OF SULFUR IN COTTON GROWN AT THREE SITES

Site	Replicate	Total radioactivity (cpm x 10^4)	Soil-derived S (mg)	Total plant S (mg)	Atmosphere-derived S (mg)
Widows Creek	1	3,486	138	168	30
	2	4,613	183	218	35
	3	2,787	111	781	670
	4	3,093	123	162	37
	Mean		(139)	(332)	(193)
Colbert (soil)	1	2,617	104	1188	1084
	2	4,544	181	437	256
	3	2,472	98	1360	1262
	4	4,373	174	1090	916
	Mean		(139)	(1019)	(880)
Colbert (sand)	1	1,454	8	622	504
	2	2,184	13	172	159
	3	1,177	7	563	556
	4	1,197	7	621	614
	Mean		(9)	(494)	(458)
Greenhouse	1	3,346	137	255	118
	2	2,311	92	311	219
	3	3,546	141	308	167
	4	3,723	148	300	152
	Mean		(130)	(294)	(164)

3 than in the other replicates. At Colbert, the lower values for total plant S in cotton grown in replicate 2 of both the soil and sand cultures were associated with lower values for atmospheric-derived S.

Fescue

Techniques I and II--The limitations of using these two methods of calculation to measure accumulation of atmospheric S were discussed above. Total vegetative production and S content of fescue (Table 11) and concentrations of the different sources of S in fescue (Table 12) were determined so that these data could be compared with the data from cotton and soybeans. Analysis of these results confirms the conclusion that these techniques have limited use as methods for measuring accumulation of atmospheric S by plants.

Technique III--The rationale for this technique was discussed above for cotton; therefore, this discussion will be limited to the calculation of data for fescue.

The specific activity of S in fescue grown at Crossville was calculated (Table 13) and used as the specific activity of soil S at all other growth sites. Note that the total plant S varied from 44 to 75 mg between replicates, but the specific activity only varied from 31.95 to 33.13 x 10^4 cpm/mg S. This shows that fertilizer S and native soil S were accumulated by the plant in the same proportion even though the total S uptake varied between replicates. The primary advantage of this technique is that the only purpose for growing plants in the absence of atmospheric S is to establish the specific activity of soil S.

The mean specific activity of S in fescue grown at Crossville (Table 13) was higher than the value calculated for cotton (Table 9). However, the mean for replicates 1, 2, and 3 for cotton was 29.21 x 10^4 cpm per milligram of S. If the soil is the only source of S, the specific activity of S in the plant should be independent of the crop species. Because cotton accumulated atmospheric S more efficiently than did fescue at the other sites, it was not unexpected that the specific activity would be lower in cotton than in fescue at Crossville. This difference in specific activities between plant species emphasizes the necessity of growing plants in the absence of atmospheric S to obtain a true specific activity of soil S.

The soil-derived S was calculated by dividing the total radioactivity in fescue grown at each site by the mean specific activity of plant S in fescue grown at Crossville (Table 14).

TABLE 11. VEGETATIVE PRODUCTION AND SULFUR CONTENT OF FESCUE GROWN AT FOUR SITES

Site	Replicate	Oven-dry weight (g)	Sulfur concentration (%)	Total plant S (mg)
Crossville	1	44	0.12	53
	2	37	0.12	44
	3	50	0.15	75
	4	39	0.14	55
	Mean	(42)	(0.13)	(57)
Widows Creek	1	64	0.18	115
	2	67	0.18	120
	3	46	0.20	92
	4	63	0.21	132
	Mean	(60)	(0.19)	(115)
Colbert (soil)	1	45	0.16	72
	2	51	0.18	92
	3	55	0.16	88
	4	48	0.19	91
	Mean	(50)	(0.17)	(86)
Colbert (sand)	1	41	0.15	62
	2	50	0.23	115
	3	49	0.17	83
	4	36	0.18	65
	Mean	(44)	(0.18)	(81)
Greenhouse	1	8	0.15	12
	2	18	0.18	32
	3	21	0.15	32
	4	11	0.09	9
	Mean	(14)	(0.14)	(21)

TABLE 12. SOURCES OF SULFUR IN FESCUE GROWN AT FIVE SITES

Site	Replicate	Radioactivity (cpm/g, dry wt)	Fertilizer S (µg/g, dry wt)	Plant S (µg/g, dry wt)	Soil S plus atmospheric S (µg/g, dry wt)
Crossville	1	399,040	233	1200	967
	2	379,996	222	1200	978
	3	480,060	281	1500	1219
	4	459,991	269	1400	1131
	Mean		(251)	(1325)	(1073)
Widows Creek	1	351,430	206	1800	1594
	2	412,750	241	1800	1555
	3	471,500	276	2000	1724
	4	423,200	247	2100	1853
	Mean		(242)	(1925)	(1683)
Colbert (soil)	1	272,160	159	1600	1441
	2	372,000	218	1800	1582
	3	387,720	226	1600	1374
	4	431,730	252	1900	1648
	Mean		(214)	(1725)	(1511)
Colbert (sand)	1	124,230	73	1500	1427
	2	441,600	258	2300	2042
	3	369,360	216	1700	1484
	4	310,000	181	1800	1629
	Mean		(182)	(1825)	(1643)
Greenhouse	1	421,200	246	1500	1254
	2	409,500	239	1800	1561
	3	282,720	165	1500	1335
	4	20,160	12	900	888
	Mean		(165)	(1425)	(1260)

TABLE 13. SPECIFIC ACTIVITY OF PLANT SULFUR FOR FESCUE GROWN AT CROSSVILLE

Replicate	Total radioactivity (cpm x 10^4)	Total plant S (mg)	Specific activity (cpm x 10^4/mg S)
1	1756	53	33.13
2	1406	44	31.95
3	2400	75	32.00
4	1794	55	32.62
Mean			(32.42)

TABLE 14. SOURCE OF SULFUR IN FESCUE GROWN AT THREE SITES

Site	Replicate	Total radioactivity (cpm x 10^4)	Soil-derived S (mg)	Total plant S (mg)	Atmosphere-derived S (mg)
Widows Creek	1	2,249	69	115	46
	2	2,765	85	120	35
	3	2,169	67	92	25
	4	2,661	82	132	50
	Mean		(76)	(115)	(39)
Colbert (soil)	1	1,225	38	72	34
	2	1,897	59	92	33
	3	2,130	67	88	21
	4	2,072	64	91	27
	Mean		(57)	(86)	(29)
Colbert (sand)	1	509	3	62	59
	2	2,208	13	115	102
	3	1,810	11	83	72
	4	1,116	7	65	58
	Mean		(8)	(81)	(73)
Greenhouse	1	337	10	12	2
	2	737	23	32	9
	3	594	18	32	14
	4	22	0.7	9	8
	Mean		(13)	(21)	(8)

General Discussion

The primary objective of this experiment was to select a technique for measuring the accumulation of S by plants, but other significant observations should be considered. The data from cotton and fescue were summarized with the source of plant S calculated by technique III (Table 15).

Cotton was more efficient than fescue in accumulating S from the atmosphere, as shown by the higher concentration of atmospheric S in cotton than in fescue grown at each site. These data suggest that the amount of S accumulated from the atmosphere was influenced by the relationship between the supply of soil S and the S requirement of the crop. Cotton has a relatively high S requirement, and the soil supply was not sufficient to maintain the S concentration above the "critical" concentration of 0.20 percent in the cotton grown at Crossville. Because the supply of soil S was limiting, the cotton grown near the coal-fired power plants accumulated more S from the atmosphere than from the soil and therefore acted as a "sink" for atmospheric S. In both the soil and sand at Colbert, the supply of S in the growth medium was limiting, and the concentrations of atmospheric S in the cotton were similar.

Fescue has a lower S requirement than cotton; therefore, the supply of soil S relative to the S requirement was higher for fescue than for cotton. Because the supply of soil S was more nearly adequate to meet the S requirement of fescue, the capacity to accumulate additional S from the atmosphere was less for fescue than for cotton. Fescue grown near the power plants accumulated more S from the soil than from the atmosphere. Further evidence of this relationship was obtained by comparing accumulation of atmospheric S by fescue grown in soil with that by fescue grown in sand at Colbert. Fescue grown in soil accumulated 57 mg S from the soil, but only 29 mg S from the atmosphere, and the concentration of atmospheric S in the plant was 58 mg/g (dry wt). Fescue grown in sand, with a low S supply, accumulated only 8 mg S from the growth medium, but 73 mg S from the atmosphere, and the concentration of atmospheric S in the plant was 165 mg/g (dry wt). Fescue acted as a "sink" for atmospheric S, as did cotton, only when the supply in the growth medium was low relative to the S requirement of the plant.

Cotton and fescue were grown in the greenhouse to measure S accumulation from the soil in the absence of atmospheric S. The accumulation of 102 and 57 mg of atmospheric S per 100 g (dry wt) by cotton and fescue, respectively, shows why the total S content of these crops could not be used as an estimate of the soil-derived S in plants. This technique does not differentiate between a higher rate of S mineralization and the atmosphere as the source of "atmospheric S" in greenhouse plants, but in either case, the specific activity of S in the greenhouse plants was not the same as the specific activity of soil S at the other growth sites. Plants grown in the absence of atmospheric S and in soil with the same rate of S mineralization rate as that in the field are required to quantify the accumulation of atmospheric S by plants. In this report, only the amount of S accumulated from the atmosphere by cotton and fescue grown near the power plants in excess of atmospheric S accumulated at Crossville was calculated.

TABLE 15. VEGETATIVE PRODUCTION, SULFUR CONTENT, AND SOURCE OF PLANT SULFUR FOR COTTON AND FESCUE GROWN AT FOUR SITES

Growth site	Oven-dry weight (g)	Sulfur concentration (%)	Total sulfur (mg)	Source of plant sulfur		
				Soil (mg)	Atmosphere (mg)	Atmosphere (mg/100 g, dry wt)
			Cotton			
Crossville	117	0.12	152	152	0	0
Widows Creek	154	0.19	332	139	193	125
Colbert (soil)	356	0.28	1018	139	854	240
Colbert (sand)	186	0.25	494	9	485	260
Greenhouse	160	0.18	294	129	164	102
			Fescue			
Crossville	42	0.13	57	57	0	0
Widows Creek	60	0.19	115	76	39	65
Colbert (soil)	50	0.17	86	57	29	58
Colbert (sand)	44	0.18	81	8	73	165
Greenhouse	14	0.14	21	13	8	57

SULFUR-SUPPLYING CAPACITY OF SOILS

Cumulative S uptake was calculated for fescue grown in soils collected from the 0- to 30-cm depth at each site (Figure 3). The uptake rates of S by these plants were used to estimate the size of the sulfate pools and the rates of S mineralization from the soil organic matter.

Sulfur accumulation by fescue grown in the topsoil from site 4 was used to demonstrate how the two sources of S supply were separated (Figure 4). The decreasing rate of S uptake during the first 16 weeks of growth reflects the depletion of the sulfate pool. Between 16 and 27 weeks, the rate of S uptake was constant, representing the rate of S mineralization from the soil organic matter. The size of the sulfate pool in the 6 kg of soil at the beginning of the experiment was estimated by extrapolating the linear portion of the curve to zero time and reading 33 mg S at the point of interception with the y-axis. The S-supplying capacity of the soil is equivalent to the rate of S mineralization and was estimated by calculating the slope of the linear portion of the S accumulation curve. The topsoil from site 4 supplied 1 mg S per kilogram of soil during the 27 weeks of growth. At this rate of S mineralization into the sulfate pool, it would take about 3 years to replenish the sulfate pool to its original level.

Although size of the sulfate pools varied between the different soils, the rates of S mineralization were similar for topsoils collected at sites 1, 3, 4, 5, and 7 (Figure 3). The relatively large sulfate pools in soil collected from sites 2 and 6 were not depleted during the growth period, and this prevented a determination of rates of S mineralization for these two soils.

Cumulative S uptake was calculated for fescue grown in soils collected from the 30- to 60-cm depth at each site (Figures 5 and 6). The sulfate pools at this depth were larger than in the corresponding 0- to 30-cm depth. This observation is consistent with results reported by Bardsley and Kilmer,[15] who used chemical analysis to assay available sulfate in soils. They found that, in 17 of 21 soils studied, acetate-soluble sulfate accumulated between the 30- and 60-cm depth. In this experiment, the sulfate pools were not depleted in soils collected from the 30- to 60-cm depth; consequently, neither the size of the sulfate pools nor the rates of S mineralization could be calculated.

The soil was removed from the greenhouse pots, and plant residue was removed; the soil was repotted and planted to fescue. The procedure used in this experiment will be repeated to deplete the sulfate pool and measure the rate of S-supplying capacity of these soils.

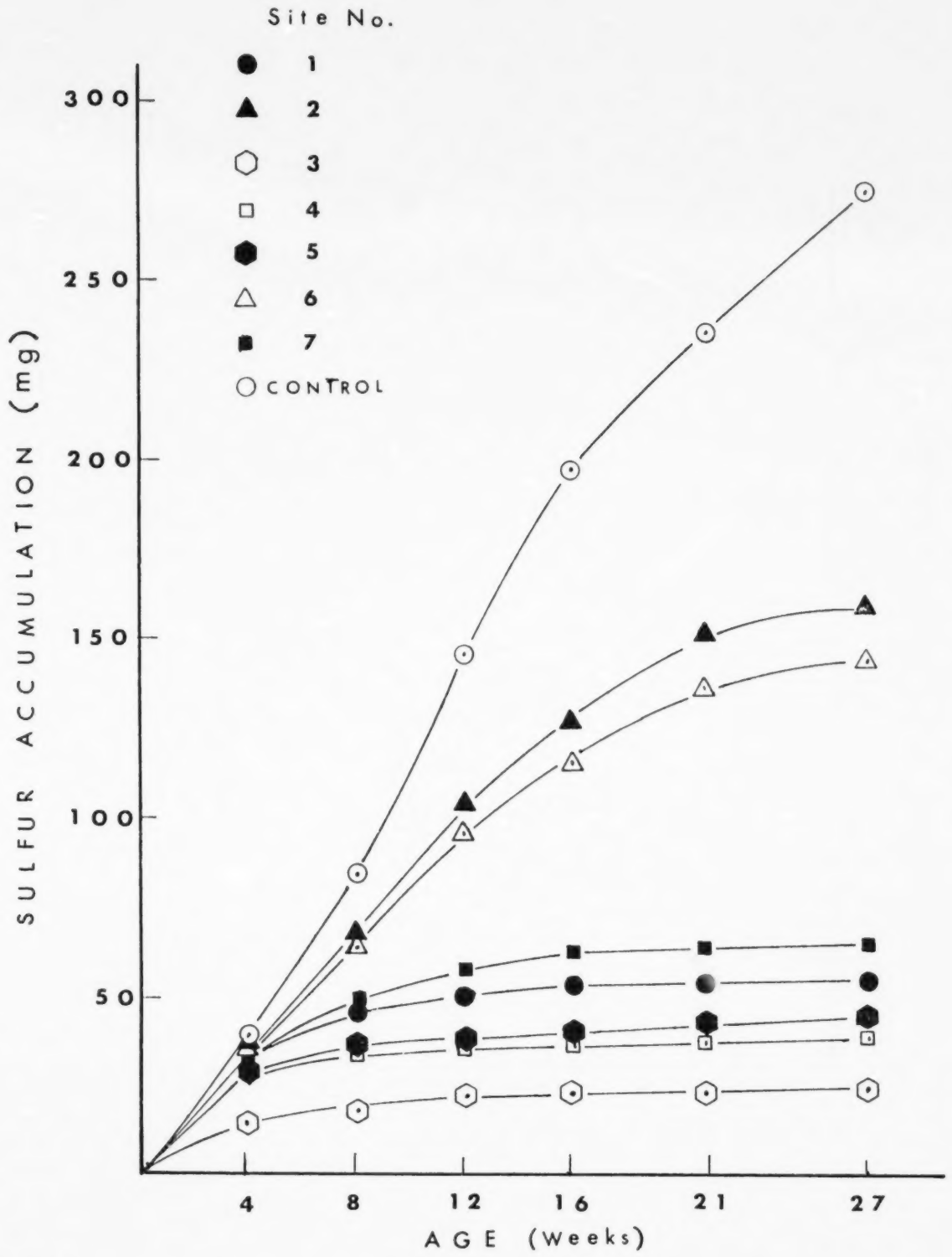

Figure 3. Sulfur accumulation by fescue grown in soil collected from the 0- to 30-cm depth.

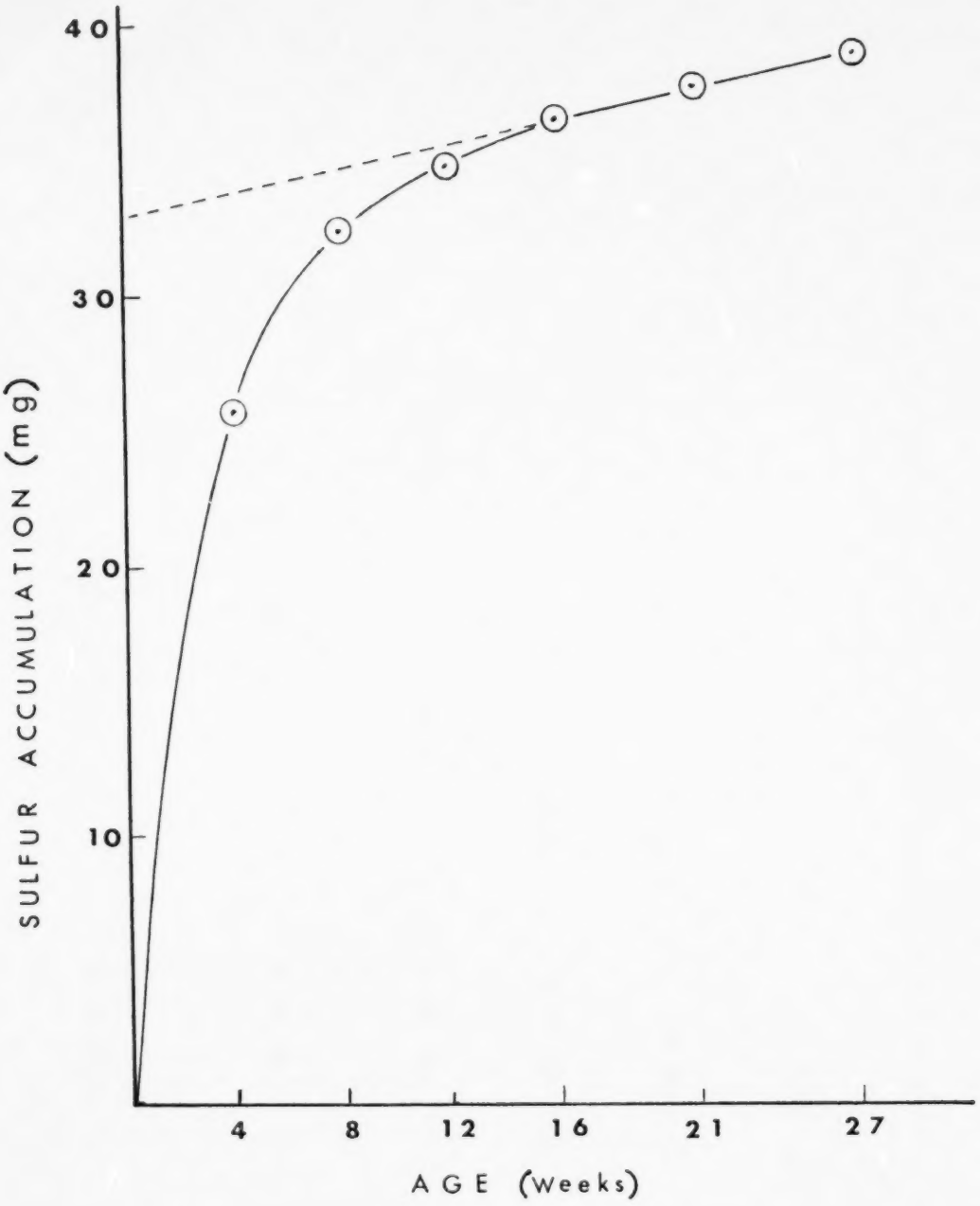

Figure 4. Sulfur accumulation by fescue grown in soil collected from the 0- to 30-cm depth at site 4.

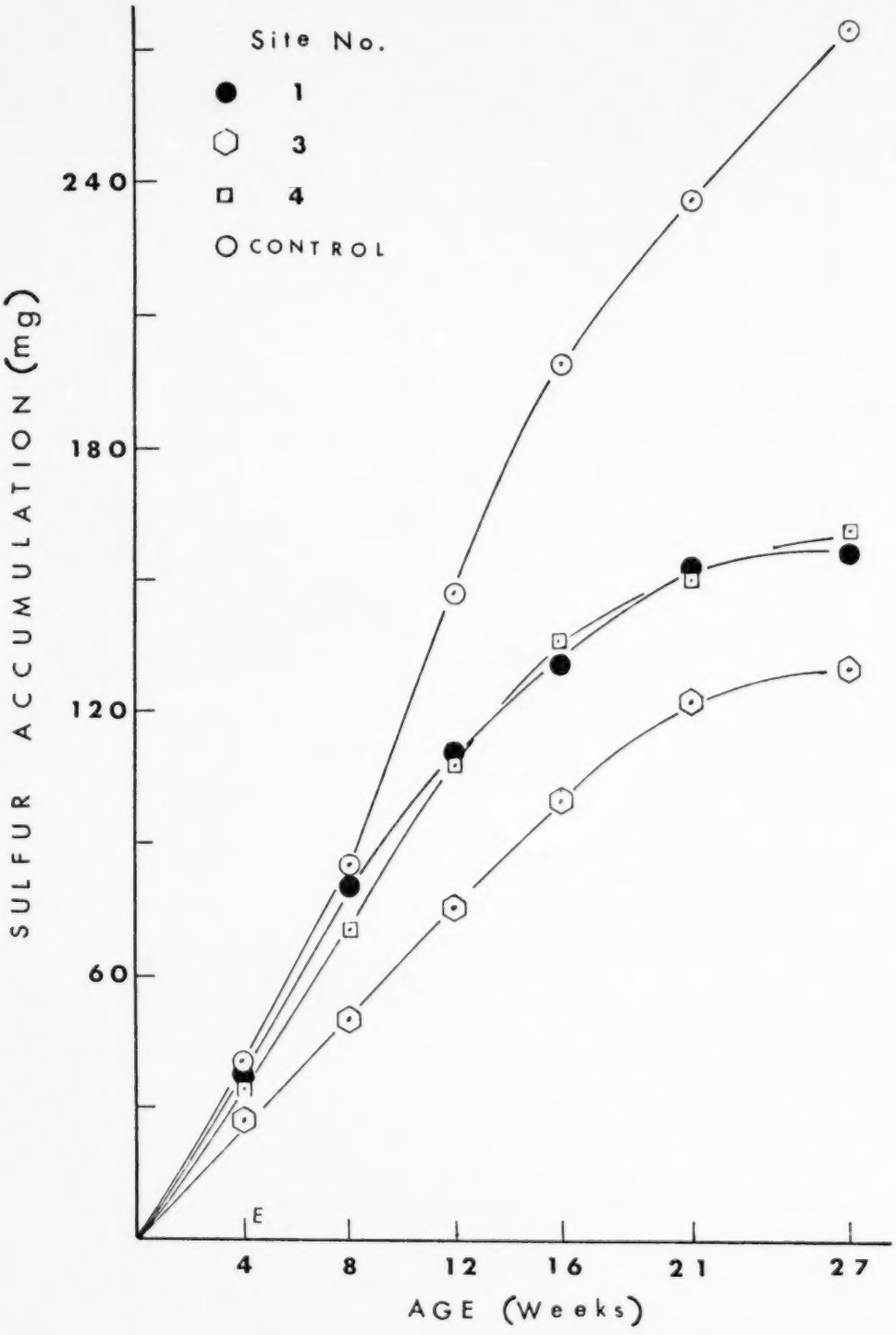

Figure 5. Sulfur accumulation in fescue grown in soil collected from the 30- to 60-cm depth at three sites.

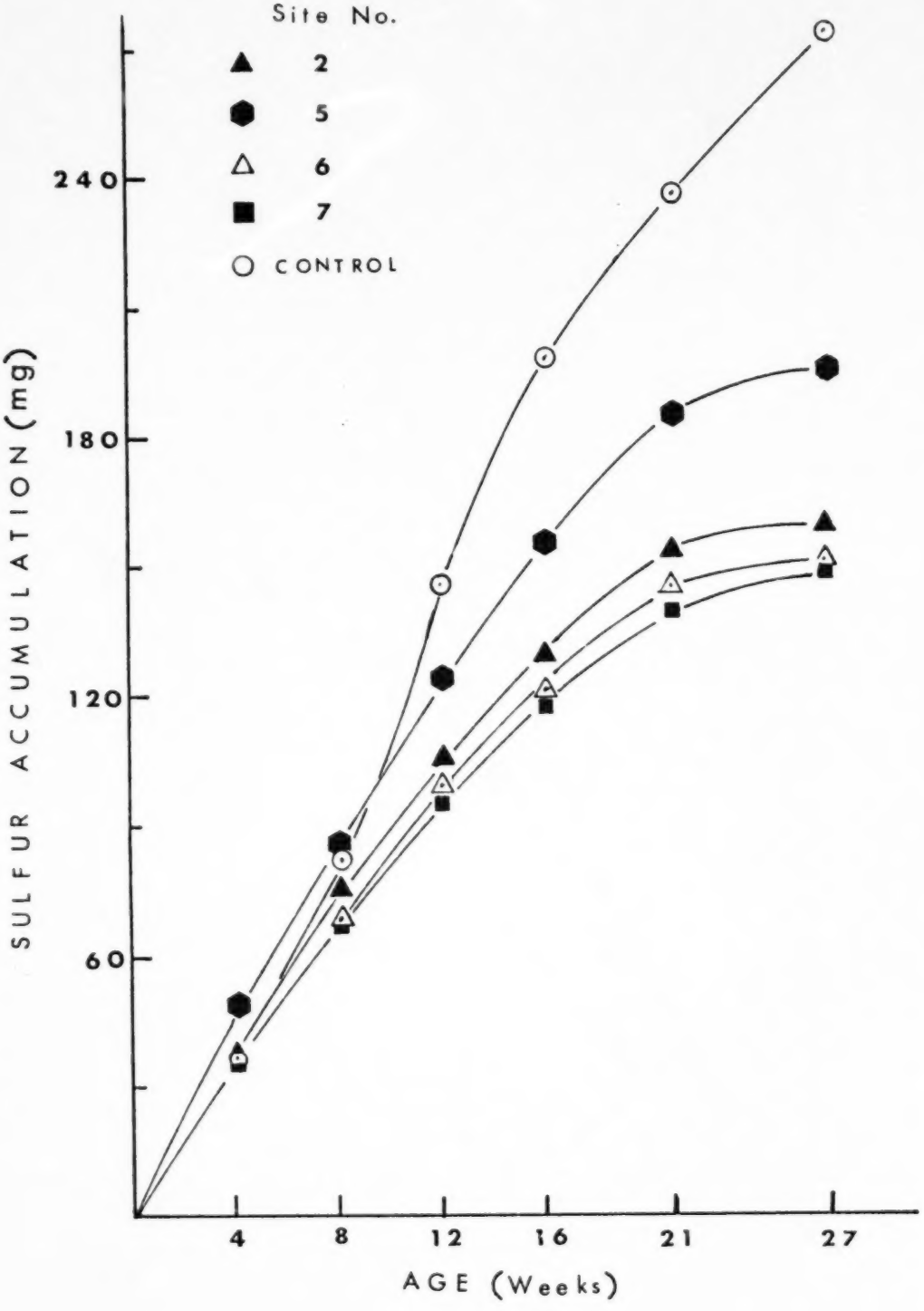

Figure 6. Sulfur accumulation in fescue grown in soil collected from the 30- to 60-cm depth at four sites.

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